- Robert Hanson, Professor Emeritus, University of Michigan
- Charles Thornton, Co-Chairman and Managing Principal, The Thornton-Tomasetti Group, Inc.
- Kathleen Tierney, Director, Natural Hazards Research and Applications Information Center, University of Colorado at Boulder
- Forman Williams, Director, Center for Energy Research, University of California at San Diego

This National Construction Safety Team Advisory Committee provided technical advice during the Investigation and commentary on drafts of the Investigation reports prior to their public release. NIST has benefited from the work of many people in the preparation of these reports, including the National Construction Safety Team Advisory Committee. The content of the reports and recommendations, however, are solely the responsibility of NIST.

Public Outreach

During the course of this Investigation, NIST held public briefings and meetings (listed in Table P–2) to solicit input from the public, present preliminary findings, and obtain comments on the direction and progress of the Investigation from the public and the Advisory Committee.

NIST maintained a publicly accessible Web site during this Investigation at http://wtc.nist.gov. The site contained extensive information on the background and progress of the Investigation.

NIST's WTC Public-Private Response Plan

The collapse of the WTC buildings has led to broad reexamination of how tall buildings are designed, constructed, maintained, and used, especially with regard to major events such as fires, natural disasters, and terrorist attacks. Reflecting the enhanced interest in effecting necessary change, NIST, with support from Congress and the Administration, has put in place a program, the goal of which is to develop and implement the standards, technology, and practices needed for cost-effective improvements to the safety and security of buildings and building occupants, including evacuation, emergency response procedures, and threat mitigation.

The strategy to meet this goal is a three-part, NIST-led, public-private response program that includes:

- A federal building and fire safety investigation to study the most probable factors that contributed to post-aircraft impact collapse of the WTC towers and the 47-story WTC 7 building, and the associated evacuation and emergency response experience.
- A research and development (R&D) program to (a) facilitate the implementation of recommendations resulting from the WTC Investigation, and (b) provide the technical basis for cost-effective improvements to national building and fire codes, standards, and practices that enhance the safety of buildings, their occupants, and emergency responders.

Table P–2. Public meetings and briefings of the WTC Investigation.

Date	Location	Principal Agenda
June 24, 2002	New York City, NY	Public meeting: Public comments on the *Draft Plan* for the pending WTC Investigation.
August 21, 2002	Gaithersburg, MD	Media briefing announcing the formal start of the Investigation.
December 9, 2002	Washington, DC	Media briefing on release of the *Public Update* and NIST request for photographs and videos.
April 8, 2003	New York City, NY	Joint public forum with Columbia University on first-person interviews.
April 29–30, 2003	Gaithersburg, MD	NCST Advisory Committee meeting on plan for and progress on WTC Investigation with a public comment session.
May 7, 2003	New York City, NY	Media briefing on release of *May 2003 Progress Report.*
August 26–27, 2003	Gaithersburg, MD	NCST Advisory Committee meeting on status of the WTC investigation with a public comment session.
September 17, 2003	New York City, NY	Media and public briefing on initiation of first-person data collection projects.
December 2–3, 2003	Gaithersburg, MD	NCST Advisory Committee meeting on status and initial results and release of the *Public Update* with a public comment session.
February 12, 2004	New York City, NY	Public meeting on progress and preliminary findings with public comments on issues to be considered in formulating final recommendations.
June 18, 2004	New York City, NY	Media/public briefing on release of *June 2004 Progress Report.*
June 22–23, 2004	Gaithersburg, MD	NCST Advisory Committee meeting on the status of and preliminary findings from the WTC Investigation with a public comment session.
August 24, 2004	Northbrook, IL	Public viewing of standard fire resistance test of WTC floor system at Underwriters Laboratories, Inc.
October 19–20, 2004	Gaithersburg, MD	NCST Advisory Committee meeting on status and near complete set of preliminary findings with a public comment session.
November 22, 2004	Gaithersburg, MD	NCST Advisory Committee discussion on draft annual report to Congress, a public comment session, and a closed session to discuss pre-draft recommendations for WTC Investigation.
April 5, 2005	New York City, NY	Media and public briefing on release of the probable collapse sequence for the WTC towers and draft reports for the projects on codes and practices, evacuation, and emergency response.
June 23, 2005	New York City, NY	Media and public briefing on release of all draft reports for the WTC towers and draft recommendations for public comment.
September 12–13, 2005	Gaithersburg, MD	NCST Advisory Committee meeting on disposition of public comments and update to draft reports for the WTC towers.
September 13–15, 2005	Gaithersburg, MD	WTC Technical Conference for stakeholders and technical community for dissemination of findings and recommendations and opportunity for the public to make technical comments.

- A dissemination and technical assistance program (DTAP) to (a) engage leaders of the construction and building community in ensuring timely adoption and widespread use of proposed changes to practices, standards, and codes resulting from the WTC Investigation and the R&D program, and (b) provide practical guidance and tools to better prepare facility owners, contractors, architects, engineers, emergency responders, and regulatory authorities to respond to future disasters.

The desired outcomes are to make buildings, occupants, and first responders safer in future disaster events.

National Construction Safety Team Reports on the WTC Investigation

This report covers the WTC towers, with a separate report on the 47-story WTC 7. Supporting documentation of the techniques and technologies used in the reconstruction are in a set of companion reports that provide more detailed documentation of the Investigation findings and the means by which these technical results were achieved. As such, they are part of the archival record of this Investigation. The titles of the full set of Investigation publications are listed in Appendix B.

EXECUTIVE SUMMARY

E.1 GENESIS OF THIS INVESTIGATION

On August 21, 2002, the National Institute of Standards and Technology (NIST) announced its building and fire safety investigation of the World Trade Center (WTC) disaster.[1] This WTC Investigation was then conducted under the authority of the National Construction Safety Team (NCST) Act, which was signed into law on October 1, 2002. A copy of the Public Law is included in Appendix A.

The goals of the investigation of the WTC disaster were:

- To investigate the building construction, the materials used, and the technical conditions that contributed to the outcome of the WTC disaster after terrorists flew large jet-fuel laden commercial airliners into the WTC towers.
- To serve as the basis for:
  - Improvements in the way buildings are designed, constructed, maintained, and used;
  - Improved tools and guidance for industry and safety officials;
  - Recommended revisions to current codes, standards, and practices; and
  - Improved public safety

The specific objectives were:

1. Determine why and how WTC 1 and WTC 2 collapsed following the initial impacts of the aircraft and why and how WTC 7 collapsed;
2. Determine why the injuries and fatalities were so high or low depending on location, including all technical aspects of fire protection, occupant behavior, evacuation, and emergency response;
3. Determine what procedures and practices were used in the design, construction, operation, and maintenance of WTC 1, 2, and 7; and

[1] NIST is a nonregulatory agency of the U.S. Department of Commerce. The purpose of NIST investigations is to improve the safety and structural integrity of buildings in the United States, and the focus is on fact finding. NIST investigative teams are authorized to assess building performance and emergency response and evacuation procedures in the wake of any building failure that has resulted in substantial loss of life or that posed significant potential of substantial loss of life. NIST does not have the statutory authority to make findings of fault nor negligence by individuals or organizations. Further, no part of any report resulting from a NIST investigation into a building failure or from an investigation under the National Construction Safety Team Act may be used in any suit or action for damages arising out of any matter mentioned in such report (15 USC 281a, as amended by P.L. 107-231).

4. Identify, as specifically as possible, areas in current building and fire codes, standards, and practices that warrant revision.

E.2 APPROACH

To meet these goals, NIST complemented its in-house expertise with an array of specialists in key technical areas. In all, over 200 staff contributed to the Investigation. NIST and its contractors compiled and reviewed tens of thousand of pages of documents; conducted interviews with over a thousand people who had been on the scene or who had been involved with the design, construction, and maintenance of the WTC; analyzed 236 pieces of steel that were obtained from the wreckage; performed laboratory tests, measured material properties, and performed computer simulations of the sequence of events that happened from the instant of aircraft impact to the initiation of collapse for each tower.

Cooperation in obtaining the resource materials and in interpreting the results came from a large number of individuals and organizations, including The Port Authority of New York and New Jersey and its contractors and consultants; Silverstein Properties and its contractors and consultants; the City of New York and its departments; the manufacturers and fabricators of the building components; the companies that insured the WTC towers; the building tenants; the aircraft manufacturers; the airlines; the public, including survivors and family members; and the media.

The scarcity of physical evidence that is typically available in place for reconstruction of a disaster led to the following approach:

- Accumulation of copious photographic and video material. With the assistance of the media, public agencies and individual photographers, NIST acquired and organized nearly 7,000 segments of video footage, totaling in excess of 150 hours and nearly 7,000 photographs representing at least 185 photographers. This guided the Investigation Team's efforts to determine the condition of the buildings following the aircraft impact, the evolution of the fires, and the subsequent deterioration of the structure.

- Establishment of the baseline performance of the WTC towers, i.e., estimating the expected performance of the towers under normal design loads and conditions. The baseline performance analysis also helped to estimate the ability of the towers to withstand the unexpected events of September 11, 2001. Establishing the baseline performance of the towers began with the compilation and analysis of the procedures and practices used in the design, construction, operation, and maintenance of the structural, fire protection, and egress systems of the WTC towers. The additional components of the performance analysis were the standard fire resistance of the WTC truss-framed floor system, the quality and properties of the structural steels used in the towers, and the response of the WTC towers to the design gravity and wind loads.

- Simulations of the behavior of each tower on September 11, 2001, in four steps:

  1. The aircraft impact into the tower, the resulting distribution of aviation fuel, and the damage to the structure, partitions, thermal insulation materials, and building contents.

  2. The evolution of multi-floor fires.

3. The heating and consequent weakening of the structural elements by the fires.
4. The response of the damaged and heated building structure, and the progression of structural component failures leading to the initiation of the collapse of the towers.

For such complex structures and complex thermal and structural processes, each of these steps stretched the state of the technology and tested the limits of software tools and computer hardware. For example, the investigators advanced the state-of-the-art in the measurement of construction material properties and in structural finite element modeling. New modeling capability was developed for the mapping of fire-generated environmental temperatures onto the building structural components.

The output of the four-step simulations was subject to uncertainties in the as-built condition of the towers, the interior layout and furnishings, the aircraft impact, the internal damage to the towers (especially the thermal insulation for fire protection of the structural steel, which is colloquially referred to as *fireproofing*), the redistribution of the combustibles, and the response of the building structural components to the heat from the fires. To increase confidence in the simulation results, NIST used the visual evidence, eyewitness accounts from inside and outside the buildings, laboratory tests involving large fires and the heating of structural components, and formal statistical methods to identify influential parameters and quantify the variability in analysis results.

- Combination of the knowledge gained into probable collapse sequences for each tower,[2] the identification of factors that contributed to the collapse, and a list of factors that could have improved building performance or otherwise mitigated the loss of life.

- Compilation of a list of findings that respond to the first three objectives and a list of recommendations that responds to the fourth objective.

E.3 SUMMARY OF FINDINGS

Objective 1: Determine why and how WTC 1 and WTC 2 collapsed following the initial impacts of the aircraft.

- The two aircraft hit the towers at high speed and did considerable damage to principal structural components (core columns, floors, and perimeter columns) that were directly impacted by the aircraft or associated debris. However, the towers withstood the impacts and would have remained standing were it not for the dislodged insulation (fireproofing) and the subsequent multi-floor fires. The robustness of the perimeter frame-tube system and the large size of the buildings helped the towers withstand the impact. The structural system redistributed loads from places of aircraft impact, avoiding larger scale damage upon impact. The hat truss, a feature atop each tower which was intended to support a television antenna, prevented earlier collapse of the building core. In each tower, a different combination of impact damage and heat-weakened structural components contributed to the abrupt structural collapse.

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[2] The focus of the Investigation was on the sequence of events from the instant of aircraft impact to the initiation of collapse for each tower. For brevity in this report, this sequence is referred to as the "probable collapse sequence," although it includes little analysis of the structural behavior of the tower after the conditions for collapse initiation were reached and collapse became inevitable.

- In WTC 1, the fires weakened the core columns and caused the floors on the south side of the building to sag. The floors pulled the heated south perimeter columns inward, reducing their capacity to support the building above. Their neighboring columns quickly became overloaded as columns on the south wall buckled. The top section of the building tilted to the south and began its descent. The time from aircraft impact to collapse initiation was largely determined by how long it took for the fires to weaken the building core and to reach the south side of the building and weaken the perimeter columns and floors.

- In WTC 2, the core was damaged severely at the southeast corner and was restrained by the east and south walls via the hat truss and the floors. The steady burning fires on the east side of the building caused the floors there to sag. The floors pulled the heated east perimeter columns inward, reducing their capacity to support the building above. Their neighboring columns quickly became overloaded as columns on the east wall buckled. The top section of the building tilted to the east and to the south and began its descent. The time from aircraft impact to collapse initiation was largely determined by the time for the fires to weaken the perimeter columns and floor assemblies on the east and the south sides of the building. WTC 2 collapsed more quickly than WTC 1 because there was more aircraft damage to the building core, including one of the heavily loaded corner columns, and there were early and persistent fires on the east side of the building, where the aircraft had extensively dislodged insulation from the structural steel.

- The WTC towers likely would not have collapsed under the combined effects of aircraft impact damage and the extensive, multi-floor fires that were encountered on September 11, 2001, if the thermal insulation had not been widely dislodged or had been only minimally dislodged by aircraft impact.

- In the absence of structural and insulation damage, a conventional fire substantially similar to or less intense than the fires encountered on September 11, 2001, likely would not have led to the collapse of a WTC tower.

- NIST found no corroborating evidence for alternative hypotheses suggesting that the WTC towers were brought down by controlled demolition using explosives planted prior to September 11, 2001. NIST also did not find any evidence that missiles were fired at or hit the towers. Instead, photographs and videos from several angles clearly showed that the collapse initiated at the fire and impact floors and that the collapse progressed from the initiating floors downward, until the dust clouds obscured the view.

Objective 2: Determine why the injuries and fatalities were so high or low depending on location, including all technical aspects of fire protection, occupant behavior, evacuation, and emergency response.

- Approximately 87 percent of the estimated 17,400 occupants of the towers, and 99 percent of those located below the impact floors, evacuated successfully. In WTC 1, where the aircraft destroyed all escape routes, 1,355 people were trapped in the upper floors when the building collapsed. One hundred seven people who were below the impact floors did not survive. Since the flow of people from the building had slowed considerably 20 min before the tower collapsed, the stairwell capacity was adequate to evacuate the occupants on that morning.

- In WTC 2, before the second aircraft strike, about 3,000 people got low enough in the building to escape by a combination of self-evacuation and use of elevators. The aircraft destroyed the operation of the elevators and the use of two of the three stairways. Eighteen people from above the impact zone found a passage through the damaged third stairway (Stairwell A) and escaped. The other 619 people in or above the impact zone perished. Eleven people who were below the impact floors did not survive. As in WTC 1, shortly before collapse, the flow of people from the building had slowed considerably, indicating that the stairwell capacity was adequate that morning.

- About 6 percent of the survivors described themselves as mobility impaired, with recent injury and chronic illness being the most common causes; few, however, required a wheelchair. Among the 118 decedents below the aircraft impact floors, investigators identified seven who were mobility impaired, but were unable to determine the mobility capability of the remaining 111.

- A principal factor limiting the loss of life was that the buildings were one-third to one-half occupied at the time of the attacks. NIST estimated that if the towers had been fully occupied with 20,000 occupants each, it would have taken just over 3 hours to evacuate the buildings and about 14,000 people might have perished because the stairwell capacity would not have been sufficient to evacuate that many people in the available time. Egress capacity required by current building codes is determined by single floor calculations that are independent of building height and does not consider the time for full building evacuation.

- Due to the presence of assembly use spaces at the top of each tower (Windows on the World restaurant complex in WTC 1 and the Top of the World observation deck in WTC 2) that were designed to accommodate over 1,000 occupants per floor, the New York City Building Code would have required a minimum of four independent means of egress (stairs), one more than the three that were available in the buildings. Given the low occupancy level on September 11, 2001, NIST found that the issue of egress capacity from these places of assembly, or from elsewhere in the buildings, was not a significant factor on that day. It is conceivable that such a fourth stairwell, depending on its location and the effects of aircraft impact on its functional integrity, could have remained passable, allowing evacuation by an unknown number of additional occupants from above the floors of impact. If the buildings had been filled to their capacity with 20,000 occupants, the required fourth stairway would likely have mitigated the insufficient egress capacity for conducting a full building evacuation within the available time.

- Evacuation was assisted by participation in fire drills within the previous year by two-thirds of survivors and perhaps hindered by a Local Law that prevented employers from *requiring* occupants to practice using the stairways. The stairways were not easily navigated in some locations due to their design, which included "transfer hallways," where evacuees had to traverse from one stairway to another location where the stairs continued. Additionally, many occupants were unprepared for the physical challenge of full building evacuation.

- The functional integrity and survivability of the stairwells was affected by the separation of the stairwells and the structural integrity of stairwell enclosures. In the impact region of WTC 1, the stairwell separation was the smallest over the building height—clustered well

within the building core—and all stairwells were destroyed by the aircraft impact. By contrast, the separation of stairwells in the impact region of WTC 2 was the largest over the building height—located along different boundaries of the building core—and one of three stairwells remained marginally passable after the aircraft impact. The shaft enclosures were fire rated but were not required to have structural integrity under typical accidental loads: there were numerous reports of stairwells obstructed by fallen debris from damaged enclosures.

- The active fire safety systems (sprinklers, smoke purge, fire alarms, and emergency occupant communications) were designed to meet or exceed current practice. However, with the exception of the evacuation announcements, they played no role in the safety of life on September 11 because the water supplies to the sprinklers were damaged by the aircraft impact. The smoke purge systems operated under the direction of the fire department after fires were not turned on, but they also would have been ineffective due to aircraft damage. The violence of the aircraft impact served as its own alarm. In WTC 2, contradictory public address announcements contributed to occupant confusion and some delay in occupants beginning to evacuate.

- For the approximately 1,000 emergency responders on the scene, this was the largest disaster they had even seen. Despite attempts by the responding agencies to work together and perform their own tasks, the extent of the incident was well beyond their capabilities. Communications were erratic due to the high number of calls and the inadequate performance of some of the gear. Even so, there was no way to digest, test for accuracy, and disseminate the vast amount of information being received. Their jobs were complicated by the loss of command centers in WTC 7 and then in the towers after WTC 2 collapsed. With nearly all elevator service disrupted and progress up the stairs taking about 2 min per floor, it would have taken hours for the responders to reach their destinations, assist survivors, and escape had the towers not collapsed.

Objective 3: Determine what procedures and practices were used in the design, construction, operation, and maintenance of WTC 1 and WTC 2.

- Because of The Port Authority's establishment under a clause of the United States Constitution, its buildings were not subject to any state or local building regulations. The buildings were unlike any others previously built, both in their height and in their innovative structural features. Nevertheless, the actual design and approval process produced two buildings that generally were consistent with nearly all of the provisions of the New York City Building Code and other building codes of that time that were reviewed by NIST. The loads for which the buildings were designed exceeded the New York City code requirements. The quality of the structural steels was consistent with the building specifications. The departures from the building codes and standards identified by NIST did not have a significant effect on the outcome of September 11.

- For the floor systems, the fire rating and insulation thickness used on the floor trusses, which together with the concrete slab served as the main source of support for the floors, were of concern from the time of initial construction. NIST found no technical basis or test data on which the thermal protection of the steel was based. On September 11, 2001, the minimum

specified thickness of the insulation was adequate to delay heating of the trusses; the amount of insulation dislodged by the aircraft impact, however, was sufficient to cause the structural steel to be heated to critical levels.

- Based on four standard fire resistance tests that were conducted under a range of insulation and test conditions, NIST found the fire rating of the floor system to vary between 3/4 hour and 2 hours; in all cases, the floors continued to support the full design load without collapse for over 2 hours.

- The wind loads used for the WTC towers, which governed the structural design of the external columns and provided the baseline capacity of the structures to withstand abnormal events such as major fires or impact damage, significantly exceeded the requirements of the New York City Building Code and other building codes of the day that were reviewed by NIST. Two sets of wind load estimates for the towers obtained by independent commercial consultants in 2002, however, differed by as much as 40 percent. These estimates were based on wind tunnel tests conducted as part of insurance litigation unrelated to the Investigation.

E.4 RECOMMENDATIONS

The tragic consequences of the September 11, 2001, attacks were directly attributable to the fact that terrorists flew large jet-fuel laden commercial airliners into the WTC towers. Buildings for use by the general population are not designed to withstand attacks of such severity; building regulations do not require building designs to consider aircraft impact. In our cities, there has been no experience with a disaster of such magnitude, nor has there been any in which the total collapse of a high-rise building occurred so rapidly and with little warning.

While there were unique aspects to the design of the WTC towers and the terrorist attacks of September 11, 2001, NIST has compiled a list of recommendations to improve the safety of tall buildings, occupants, and emergency responders based on its investigation of the procedures and practices that were used for the WTC towers; these procedures and practices are commonly used in the design, construction, operation, and maintenance of buildings under normal conditions. Public officials and building owners will need to determine appropriate performance requirements for those tall buildings, and selected other buildings, that are at higher risk due to their iconic status, critical function, or design.

The topics of the recommendations in eight groups are listed in Table E–1. The ordering does not reflect any priority.

The eight major groups of recommendations are:

- Increased Structural Integrity: The standards for estimating the load effects of potential hazards (e.g., progressive collapse, wind) and the design of structural systems to mitigate the effects of those hazards should be improved to enhance structural integrity.

- Enhanced Fire Endurance of Structures: The procedures and practices used to ensure the fire endurance of structures should be enhanced by improving the technical basis for construction classifications and fire resistance ratings, improving the technical basis for standard fire resistance testing methods, use of the "structural frame" approach to fire resistance ratings,

and developing in-service performance requirements and conformance criteria for sprayed fire-resistive material.

- New Methods for Fire Resistant Design of Structures: The procedures and practices used in the fire resistant design of structures should be enhanced by requiring an objective that uncontrolled fires result in burnout without local or global collapse. Performance-based methods are an alternative to prescriptive design methods. This effort should include the development and evaluation of new fire resistive coating materials and technologies and evaluation of the fire performance of conventional and high-performance structural materials.

- Improved Active Fire Protection: Active fire protection systems (i.e., sprinklers, standpipes/ hoses, fire alarms, and smoke management systems) should be enhanced through improvements to design, performance, reliability, and redundancy of such systems.

- Improved Building Evacuation: Building evacuation should be improved to include system designs that facilitate safe and rapid egress, methods for ensuring clear and timely emergency communications to occupants, better occupant preparedness for evacuation during emergencies, and incorporation of appropriate egress technologies.

- Improved Emergency Response: Technologies and procedures for emergency response should be improved to enable better access to buildings, response operations, emergency communications, and command and control in large-scale emergencies.

- Improved Procedures and Practices: The procedures and practices used in the design, construction, maintenance, and operation of buildings should be improved to include encouraging code compliance by nongovernmental and quasi-governmental entities, adoption and application of egress and sprinkler requirements in codes for existing buildings, and retention and availability of building documents over the life of a building.

- Education and Training: The professional skills of building and fire safety professionals should be upgraded though a national education and training effort for fire protection engineers, structural engineers, architects, and building regulatory and fire service personnel.

The recommendations call for action by specific entities regarding standards, codes and regulations, their adoption and enforcement, professional practices, education, and training; and research and development. Only when each of the entities carries out its role will the implementation of a recommendation be effective.

The recommendations do not prescribe specific systems, materials, or technologies. Instead, NIST encourages competition among alternatives that can meet performance requirements. The recommendations also do not prescribe specific threshold levels; NIST believes that this responsibility properly falls within the purview of the public policy setting process, in which the standards and codes development process plays a key role.

NIST believes the recommendations are realistic and achievable within a reasonable period of time. Only a few of the recommendations call for new requirements in standards and codes. Most of the recommendations deal with improving an existing standard or code requirement, establishing a standard

for an existing practice without one, establishing the technical basis for an existing requirement, making a current requirement risk-consistent, adopting or enforcing a current requirement, or establishing a performance-based alternative to a current prescriptive requirement.

NIST strongly urges that immediate and serious consideration be given to these recommendations by the building and fire safety communities in order to achieve appropriate improvements in the way buildings are designed, constructed, maintained, and used and in evacuation and emergency response procedures—with the goal of making buildings, occupants, and first responders safer in future emergencies.

NIST also strongly urges building owners and public officials to (1) evaluate the safety implications of these recommendations to their existing inventory of buildings and (2) take the steps necessary to mitigate any unwarranted risks without waiting for changes to occur in codes, standards, and practices.

NIST further urges state and local agencies to rigorously enforce building codes and standards since such enforcement is critical to ensure the expected level of safety. Unless they are complied with, the best codes and standards cannot protect occupants, emergency responders, or buildings.

Table E–1. Topics of NIST recommendations for improved public safety in tall and high-risk buildings.

Recommendation Group	Recommendation Topic	Responsible Community					Application		Relation to 9/11 Outcome	
		Practices	Standards, Codes, Regulations	Adoption & Enforcement	R&D/Further Study	Education & Training	All Tall Buildings	Selected Other High-Risk Buildings	Related[a]	Unrelated[b]
Increased Structural Integrity	Prevention of progressive collapse and failure analysis of complex systems	✓	✓	✓	✓	✓	✓	✓	✓	
	Estimation of wind loads and their effects on tall buildings	✓	✓		✓		✓	✓		✓
	Allowable tall buildings sway	✓	✓		✓		✓			✓
Enhanced Fire Endurance of Structures	Fire resistance rating requirements and construction classification	✓	✓		✓		✓			✓
	Fire resistance testing of building components and extrapolation of test data to qualify untested building components		✓		✓		✓			✓
	In-service performance requirements and inspection procedures for sprayed fire-resistive material (SFRM or spray-on fireproofing)	✓	✓	✓	✓		✓			✓
	"Structural frame" approach (structural members connected to columns carry the higher fire resistance rating of the columns)		✓	✓		✓	✓	✓		✓
New Methods for Fire Resistant Design of Structures	Burnout without partial or global (total) structural collapse in uncontrolled building fires	✓	✓	✓	✓	✓	✓	✓	✓	
	Performance-based design and retrofit of structures to resist fires	✓	✓		✓	✓	✓	✓		✓
	New fire-resistive coating materials, systems, and technologies	✓	✓		✓		✓	✓	✓	
	Evaluation of high performance structural materials under conditions expected in building fires	✓			✓		✓	✓		✓
Improved Active Fire Protection	Performance and redundancy of active fire protection systems to accommodate the greater risks associated with tall buildings	✓	✓		✓		✓	✓	✓	
	Advanced fire alarm and communication systems that provide continuous, reliable, and accurate information on life safety conditions to manage the evacuation process.		✓		✓		✓		✓	
	Advanced fire/emergency control panels with more reliable information from the active fire protection systems to provide tactical decision aids		✓		✓		✓	✓	✓	
	Improved transmission to emergency responders, and off-site or black box storage, of information from building monitoring systems	✓	✓		✓		✓	✓	✓	✓

Recommendation Group	Recommendation Topic	Responsible Community: Practices	Responsible Community: Standards, Codes, Regulations	Responsible Community: Adoption & Enforcement	Responsible Community: R&D/Further Study	Responsible Community: Education & Training	Application: All Tall Buildings	Application: Selected Other High-Risk Buildings	Relation to 9/11 Outcome: Related[a]	Relation to 9/11 Outcome: Unrelated[b]
Improved Building Evacuation	Public education and training campaigns to improve building occupants' preparedness for evacuation	✓	✓		✓	✓	✓		✓	✓
	Tall building design for timely full building emergency evacuation of occupants	✓	✓		✓	✓	✓	✓	✓	✓
	Design of occupant-friendly evacuation paths that maintain functionality in foreseeable emergencies	✓	✓				✓		✓	
	Planning for communication of accurate emergency information to building occupants	✓	✓			✓	✓	✓	✓	
	Evaluation of alternative evacuation technologies, to allow all occupants equal opportunity for evacuation and to facilitate emergency response access	✓	✓		✓		✓	✓	✓	
Improved Emergency Response	Fire-protected and structurally hardened elevators	✓	✓		✓		✓		✓	
	Effective emergency communications systems for large-scale emergencies	✓	✓	✓	✓	✓	✓		✓	
	Enhanced gathering, processing, and delivering of critical information to emergency responders	✓	✓	✓	✓	✓	✓	✓	✓	
	Effective and uninterrupted operation of the command and control system for large-scale building emergencies	✓	✓	✓	✓	✓	✓		✓	
Improved Procedures and Practices	Provision of code-equivalent level of safety and certification of as-designed and as-built safety by nongovernmental and quasi-governmental entities	✓	✓	✓			✓	✓		✓
	Egress and sprinkler requirements for existing buildings	✓		✓			✓	✓		✓
	Retention and off-site storage of design, construction, maintenance, and modification documents over the entire life of the building; and availability of relevant building information for use by responders in emergencies	✓	✓	✓			✓	✓	✓	
	Design professional responsibility for innovative or unusual structural and fire safety systems	✓	✓			✓	✓	✓	✓	
Education and Training	Professional cross training of fire protection engineers, architects, structural engineers, and building regulatory and fire service personnel.	✓	✓			✓	✓	✓	✓	
	Training in computational fire dynamics and thermostructural analysis	✓				✓	✓	✓		✓

a. If in place, could have changed the outcome on September 11, 2001.
b. Would not have changed the outcome, yet is an important building and fire safety issue that was identified during the course of the Investigation.

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PART I: SEPTEMBER 11, 2001

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Chapter 1
NEW YORK CITY'S WORLD TRADE CENTER

1.1 THE ORIGINATION

In 1960, American technology was on the rise, and internationalism was a prominent theme. It was in this technical and global political context and this year that the planning began for a World Trade Center (WTC) to be located in lower Manhattan. From its first conception during the 1939 World's Fair in New York, it now emerged under the powerful advocacy of the Chase Manhattan Bank's David Rockefeller. Here was a grand plan that would embody the concept of New York City as a center of world commerce and provide a home for numerous international trade companies.

The organization that would build the World Trade Center was The Port of New York Authority, later to be renamed as The Port Authority of New York and New Jersey (The Port Authority, PANYNJ). Created in 1921, under a clause in the United States Constitution, to run the multijurisdictional commercial zones in the region, The Port Authority built and operated facilities on the banks of the Port of New York's waterways, the bridges to cross them, and the major metropolitan airports. It had the authority to obtain land by eminent domain and to raise funds for its projects. Now, under the leadership of its Executive Director, Austin Tobin, the concept for the World Trade Center grew from the grand plan of David Rockefeller to the grandeur of the world's largest office complex.

To fulfill all the functional, aesthetic, and economic desires for this concept, innovative architecture was needed. In 1962, the firm of Minoru Yamasaki & Associates was hired to perform the architectural design, which was first unveiled in 1964. The team also involved Emory Roth & Sons, P.C., as the architect of record.[1] The structural engineering was by Worthington, Skilling, Helle and Christiansen. (Some time after completion of the construction, Skilling, Helle, Christiansen, and Robertson, and then Leslie E. Robertson Associates (LERA) assumed that role.) Jaros, Baum & Bolles were hired as the mechanical engineers, and Joseph R. Loring & Associates were the electrical engineers. Tishman Construction Corporation was the general contractor.

In 1966, the formal groundbreaking for the towers took place. Construction began in 1968, with the first occupancy in 1970. These dates establish the historical context for the building codes and the state of practice under which the complex was designed and constructed. This will be discussed further in Part II.

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[1] The functions of these entities are as follows. In New York City, a permit, issued by the building commissioner, is required to construct, alter, repair, demolish or remove any building. The architect who signs and generally files the plans (as part of the process for securing the permit) and takes the lead role of a project is the architect-of-record. Specific subsets of plans may be signed by the structural, electrical, and mechanical engineers, representing the separate disciplines involved in those subsets. The filed plans are reviewed and approved for compliance with the building code requirements by the building commissioner before issuance of the permit.

The City of New York had no jurisdiction. However, The Port Authority required that all the WTC tower plans be submitted for their review and approval for code compliance and other architectural requirements. The responsibility of technical correctness rested with the architect of record and the engineers of record.

The expected tenancy by companies involved in international trade did not materialize as conceived, so the State of New York, the City of New York, and The Port Authority became the principal WTC tenants in the 1970s. As the years passed, however, the prestige of the address grew, and the requirement that occupants be involved in international trade was relaxed. At the end of the twentieth century, the World Trade Center was nearly fully occupied by a diverse mixture of large and small businesses and federal, state, and city government organizations.

1.2 THE WORLD TRADE CENTER COMPLEX

1.2.1 The Site

By 2001, the WTC complex had become an integral part of Manhattan. It was composed of seven buildings (here referred to as WTC 1 through WTC 7) on a site toward the southwest tip of Manhattan Island (Figures 1–1 and 1–2). Whether viewed from close up, from the Statue of Liberty across the Upper Bay or from an aircraft descending to LaGuardia Airport, the towers were a sight to behold. The two towers, WTC 1 (North Tower) and WTC 2 (South Tower), were each 110 stories high, dwarfing the other skyscrapers in lower Manhattan and seemingly extending to all Manhattan the definition of "tall" previously set by midtown's Empire State Building. WTC 3, a Marriott Hotel, was 22 stories tall, WTC 4 (South Plaza Building) and WTC 5 (North Plaza Building) were each 9-story office buildings, and WTC 6 (U.S. Customs House) was an 8-story office building. These six buildings were built around a 5-acre Plaza named in honor of Austin Tobin. WTC 7 was a 47-story office building on Port Authority land across Vesey Street on the north side of the Plaza complex. Built over the ConEd substation serving the WTC complex, it was completed in 1987 and was operated by Silverstein Properties, Inc.

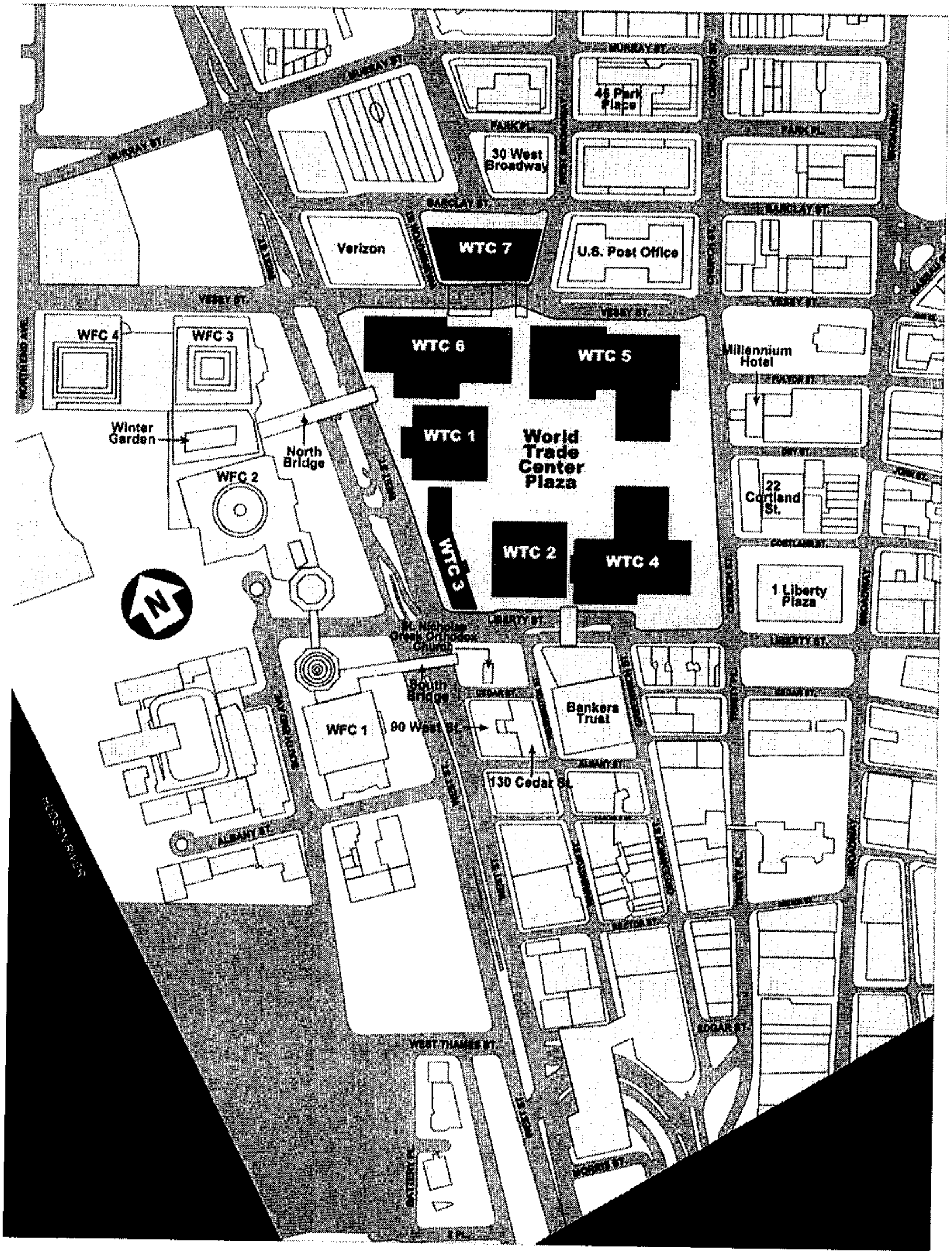
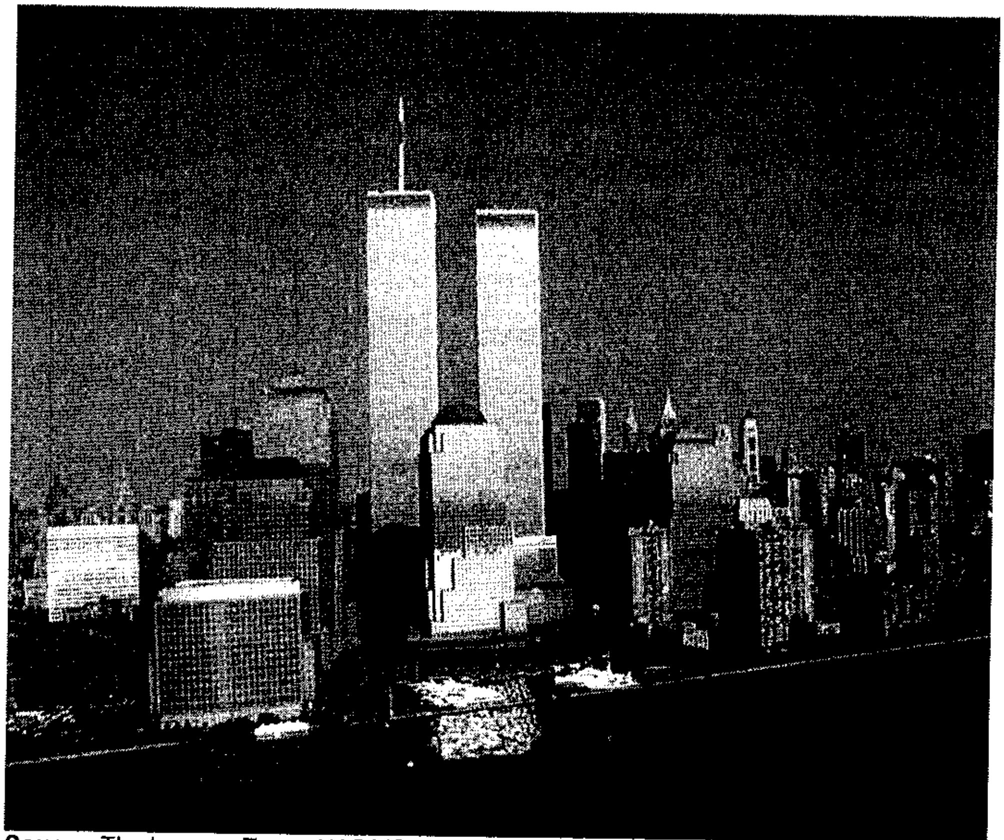


Figure 1–1. The World Trade Center in Lower Manhattan.



Source: The Imagers Team, NASA/GSFC.

Figure 1–2. Lower Manhattan and the World Trade Center towers.

Below the 11 western acres of the site, underneath a large portion of the Plaza and WTC 1, WTC 2, WTC 3, and WTC 6, was a 6-story underground structure. The structure was surrounded by a wall that extended from ground level down 70 ft to bedrock. Holding back the waters of the Hudson River, this wall had enabled rapid excavation for the foundation and continued to keep groundwater from flooding the underground levels.

Commuter trains brought tens of thousands of workers and visitors to Manhattan from Brooklyn and New Jersey into a new underground station below the plaza. A series of escalators and elevators took the WTC employees directly to an underground shopping mall and to the Concourse Level of the towers.

1.2.2 The Towers

The Buildings

The focus of the complex was on the two towers, each taller than any other building in the world at that time. The roof of WTC 1 was 1,368 ft above the Concourse Level, 6 ft taller than WTC 2, and supported a 360 ft tall antenna mast for television and radio transmission. The footprint of each tower was a square, about 210 ft on a side (approximately an acre), with the corners of the tower beveled 9 ft 9 in. Internally, each floor was a square, about 206 ft on a side.[2]

The superb vistas from the top of such buildings virtually demanded public space from which to view them, and The Port Authority responded. The 107th floor of WTC 1 housed a gourmet restaurant and bar with views of the Hudson River and New Jersey to the west, the skyscrapers of midtown Manhattan to the north, the East River and Queens and Brooklyn to the east, the Statue of Liberty to the southwest, and the Atlantic Ocean to the south. Similar views could be seen from observation decks on the 107th floor and the roof of WTC 2.

Table 1–1 shows the use of the floors, which was similar but not identical in the two towers.

Table 1–1. Use of floors in the WTC towers.

Floor(s)	WTC 1	WTC 2
Roof	Antenna space and window washing equipment	Outdoor observation deck and window washing equipment
110	Television studios	Mechanical equipment
108, 109	Mechanical equipment	Mechanical equipment
107	Windows on the World restaurant	Indoor observation deck
106	Catering	Tenant space
79 through 105	Tenant space	Tenant space
78	Skylobby, tenant space	Skylobby, tenant space
77	Tenant space	Tenant space
75, 76	Mechanical equipment	Mechanical equipment
45 through 74	Tenant space	Tenant space
44	Skylobby, cafeteria, tenant space	Skylobby, tenant space
43	Port Authority space	Tenant space
41, 42	Mechanical equipment	Mechanical equipment
9 through 40	Tenant space	Tenant space
7, 8	Mechanical floors	Mechanical floors
Concourse through 6	6-story lobby	6-story lobby

[2] Extensive details regarding all aspects of this report are found in the supporting Investigation reports listed in Appendix B. A subject index of those reports appears as Appendix C to this report. Those reports, in turn, cite the numerous documents made available to the Investigation Team. To maintain continuity, citations of the source documents are not included in this report. They are found in the supporting Investigation reports.

The Port Authority had managed the operation of the two towers since their opening three decades earlier. Silverstein Properties acquired a 99-year lease on the towers in July 2001.

The Structures

Each of the tenant floors of the towers was intended to offer a large expanse of workspace, virtually uninterrupted by columns or walls. This called for an innovative structural design, lightweight to minimize the total mass of 110 stories, yet strong enough to support the huge building with all its furnishings and people. Structural engineers refer to the building weight as the *dead load*; the people and furnishings are called the *live load.* Collectively, these are referred to as *gravity loads*. The buildings would also need to resist *lateral loads* and excessive swaying, principally from the hurricane force winds that periodically strike the eastern seaboard of the United States. An additional load, stated by The Port Authority to have been considered in the design of the towers, was the impact of a Boeing 707, the largest commercial airliner when the towers were designed, hitting the building at its full speed of 600 mph.

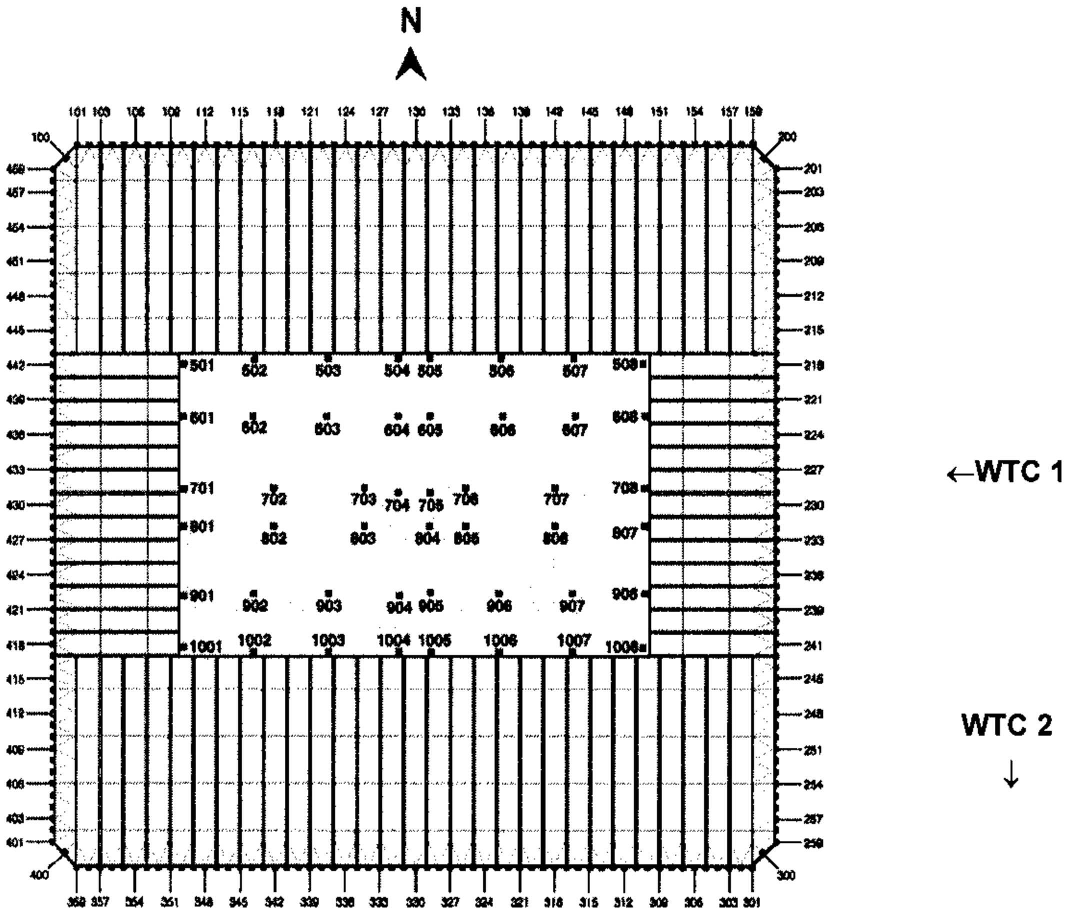
> In 1945, a B-25 aircraft had become lost in the fog and struck the 78th and 79th floors of the Empire State Building. The building withstood the impact and ensuing fire and was ready for reoccupancy the following week.

Skilling and his team rose to the challenge of providing the required load capacity within Yamasaki's design concept. They incorporated an innovative framed-tube concept for the structural system. The columns supporting the building were located both along the external faces and within the core. The core also contained the elevators, stairwells, and utility shafts. The dense array of columns along the building perimeter was to resist the lateral load due to hurricane-force winds, while also sharing the gravity loads about equally with the core columns. The floor system was to provide stiffness and stability to the framed-tube system in addition to supporting the floor loads. Extensive and detailed studies were conducted in wind tunnels, instead of relying on specific, prescriptive building code requirements, to estimate the wind loads used in the design of these buildings.[3] This approach took advantage of the allowance by most state and local building codes for alternative designs and construction if evidence were presented that ensured equivalent performance.

> A grade of steel is characterized by its yield strength, expressed in ksi, or thousands of pounds per square inch. This is the force per unit area at which the steel begins to undergo a permanent deformation. Different steel strengths, or grades, are manufactured by varying the chemistry and processing of the alloy. Higher strength steel is used when the design calls for more strength per weight of the steel column or beam.

There were four major structural subsystems in the towers, referred to as the exterior wall, the core, the floor system, and the hat truss. The first, the exterior structural subsystem, was a vertical square tube that consisted of 236 narrow columns, 59 on each face from the 10th floor to the 107th floor (Figure 1–3). There were also columns on alternate stories at each of the beveled corners, but these carried none of the gravity loads. (There were fewer, wider-spaced columns below the 7th floor to accommodate doorways.) Each column was fabricated by welding four steel plates to form a tall box, nominally 14 in. on a side. The space between the steel columns was 26 in., with a narrower,

[3] The studies showed that each tower affected the wind loads on the other. This effect was not accounted for in the prescriptive wind load requirements found in building regulations.



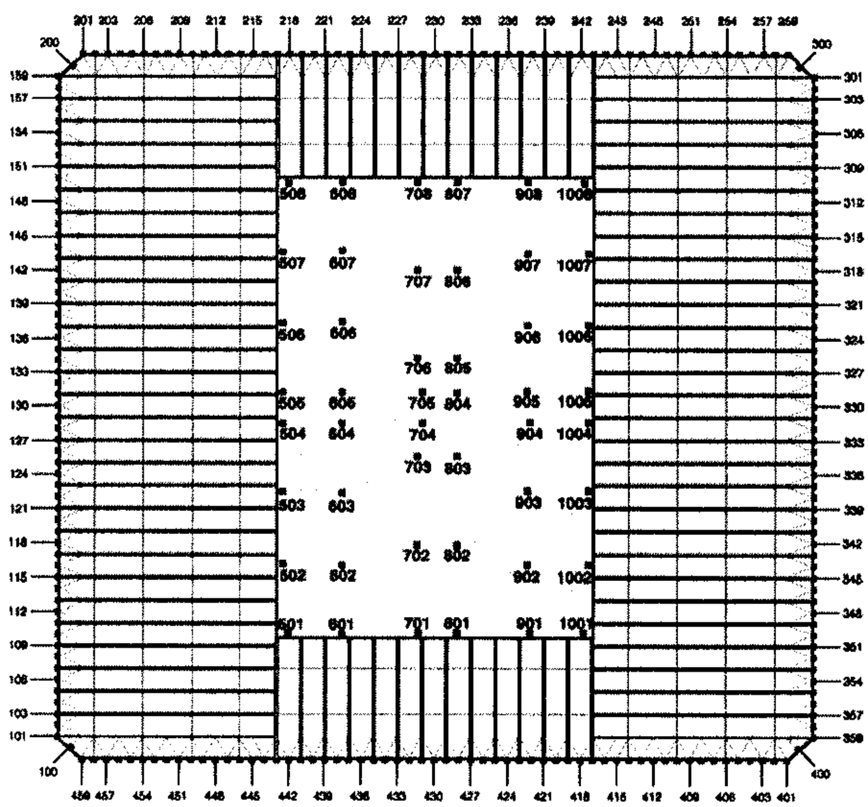
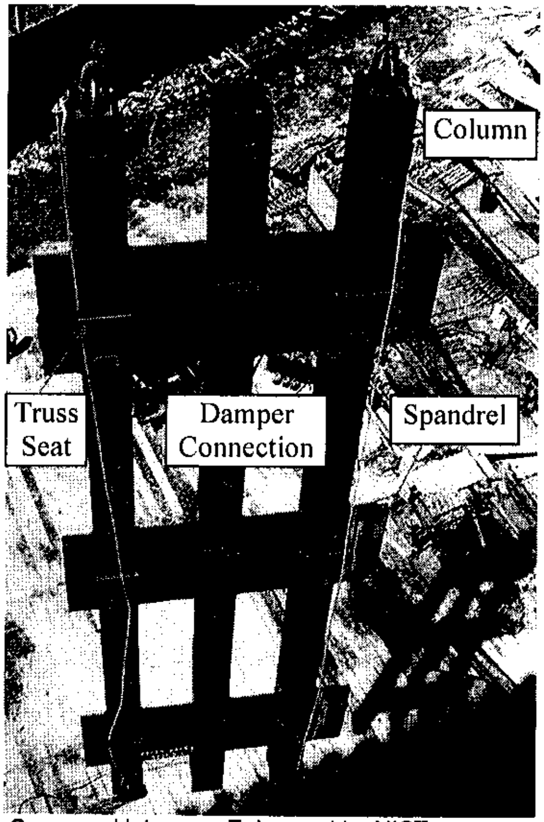
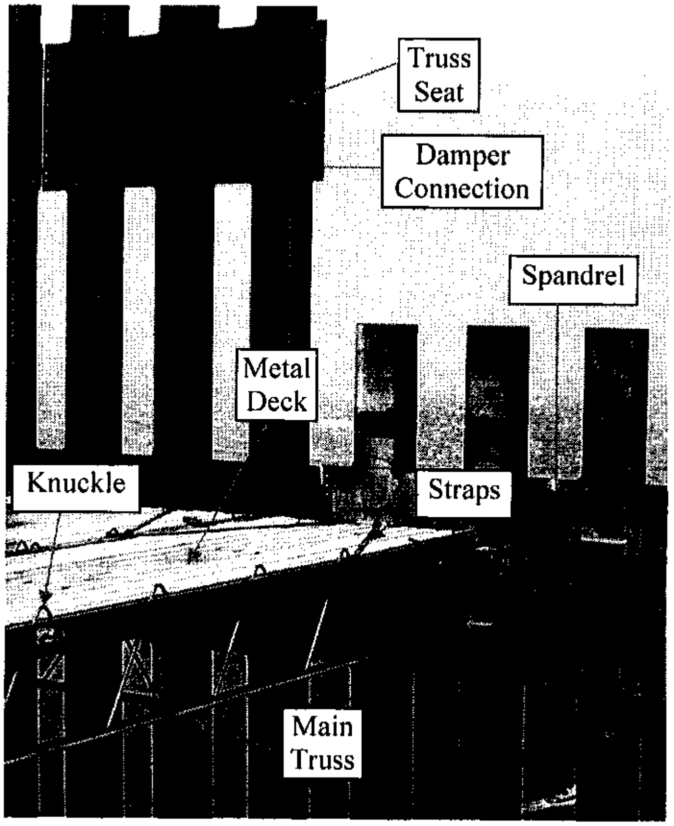


Figure 1–3. Tower floor plans with column numbers.

framed plate glass window in each gap. Adjacent columns were connected at each floor by steel spandrel plates, 52 in. high. The upper parts of the buildings had less wind load and building mass to support. Thus, on higher floors, the thickness of the steel plates making up the columns decreased, becoming as thin as ¼ in. near the top. There were 10 grades of steel used for the columns and spandrels, with yield strengths ranging from 36 ksi to 100 ksi. The grade of steel used in each location was dictated by the calculated stresses due to the gravity and wind loads.

All the exterior columns and spandrels were prefabricated into welded panels, three stories tall and three columns wide. The panels, each numbered to identify its location in the tower, were then bolted to adjacent units to form the walls (Figure 1–4). The use of identically shaped prefabricated elements was itself an innovation that enabled rapid construction. The high degree of modularization and prefabrication used in the construction of these buildings and the identification, tracking, and logistics necessary to ensure that each piece was positioned correctly was unprecedented.

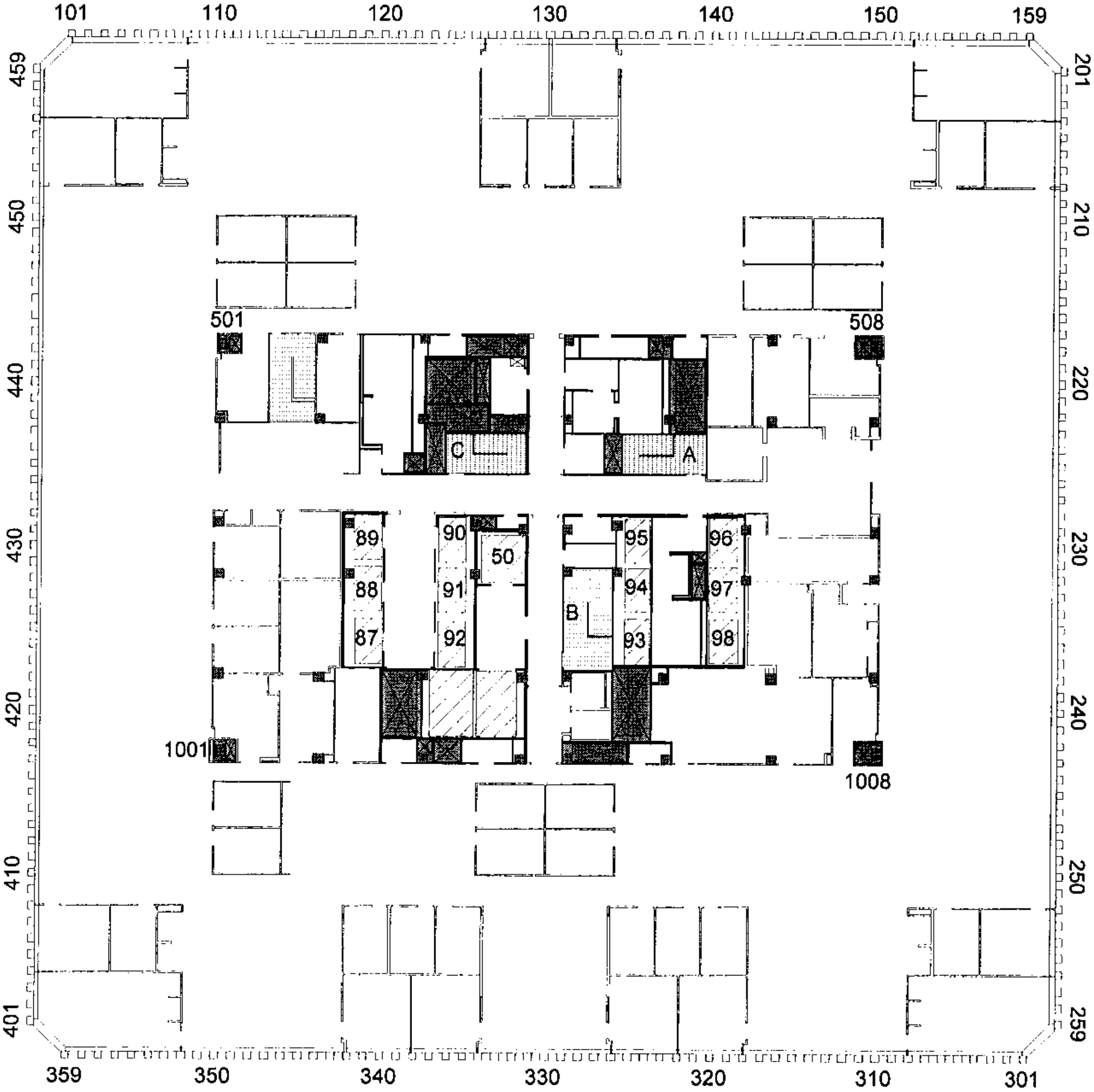




Source: Unknown. Enhanced by NIST.

Figure 1–4. Perimeter column/spandrel assembly and floor structure.

A second structural subsystem was located in a central service area, or core (Figure 1–5), approximately 135 ft by 87 ft, that extended virtually the full height of the building. The long axis of the core in WTC 1 was oriented in the east-west direction, while the long axis of the core in WTC 2 was oriented in the north-south direction (Figure 1–3). The 47 columns in this rectangular space were fabricated using primarily 36 ksi and 42 ksi steels and also decreased in size at the higher stories. The four massive corner columns bore nearly one-fifth of the total gravity load on the core columns. The core columns were interconnected by a grid of conventional steel beams to support the core floors.



Note: Column numbers are shown around the perimeter. The four corner core columns (501, 508, 1001, and 1008) are marked for orientation. Stairwells A, B, and C are shown in red stripes. The fourth red-striped area is the tenant's convenience stairwell that connected the 95th through 97th floors in WTC 1; it was not considered part of the egress system. The remaining numbers denote specific elevators. Much of the rest of the floor was open space suited for offices, conference rooms, or office cubicles. The arrangement and size of the core varied among the different floors.

Figure 1–5. Plan of the 96th floor of WTC 1 showing the core and tenant spaces.

The third major structural subsystem was the floors in the tenant spaces. These floors supported their own weight, along with live loads, provided lateral stability to the exterior walls, and distributed wind loads among the exterior walls. The floor construction was an innovation for a tall building. As shown in Figure 1–6, each tenant floor consisted of 4 in. thick, lightweight cast-in-place concrete on a fluted steel deck, but that is where "ordinary" ended. Supporting the slab was a grid of lightweight steel bar trusses. The top bends (or "knuckles") of the main truss webs extended 3 in. above the top chord and were embedded into the concrete floor slab. This concrete and steel assembly thus functioned as a composite unit, that is, the concrete slab acted integrally with the steel trusses to carry floor loads. The primary truss pairs were either 60 ft or 35 ft long and were spaced at 6 ft 8 in. There were perpendicular bridging trusses every 13 ft 4 in. The floor trusses and fluted metal deck were prefabricated in panels that were typically 20 ft wide and that were hoisted into position in a fashion similar to the exterior wall panels.

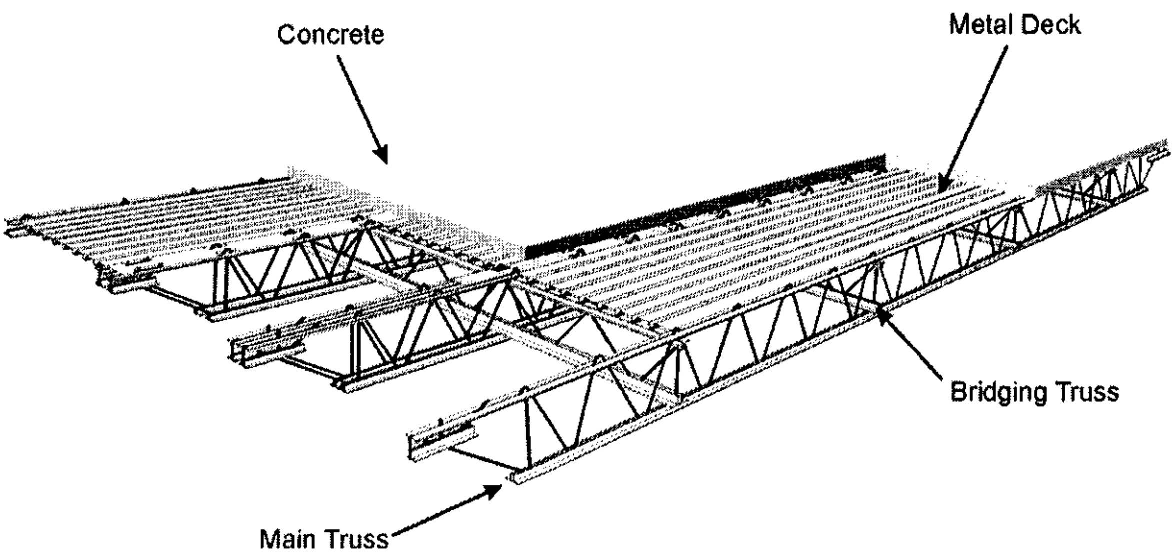


Figure 1–6. Schematic of composite floor truss system.

The bottom chords were connected to the spandrel plates by devices that were called viscoelastic dampers. Experiments on motion perception, conducted with human subjects, had shown a high potential for occupant discomfort when the building swayed in a strong wind. When the tower was buffeted by strong winds, these dampers absorbed energy, reducing the sway and the vibration expected from a building that tall. The use of such vibration damping devices in buildings was an innovation at that time.

The fourth major structural subsystem was located from the 107th floor to the roof of each tower. It was a set of steel braces, collectively referred to as the "hat truss" (Figure 1–7). Its primary purpose had been to support a tall antenna atop each tower, although only WTC 1 had one installed. The hat truss provided additional connections among the core columns and between the core and perimeter columns, providing additional means for load redistribution.

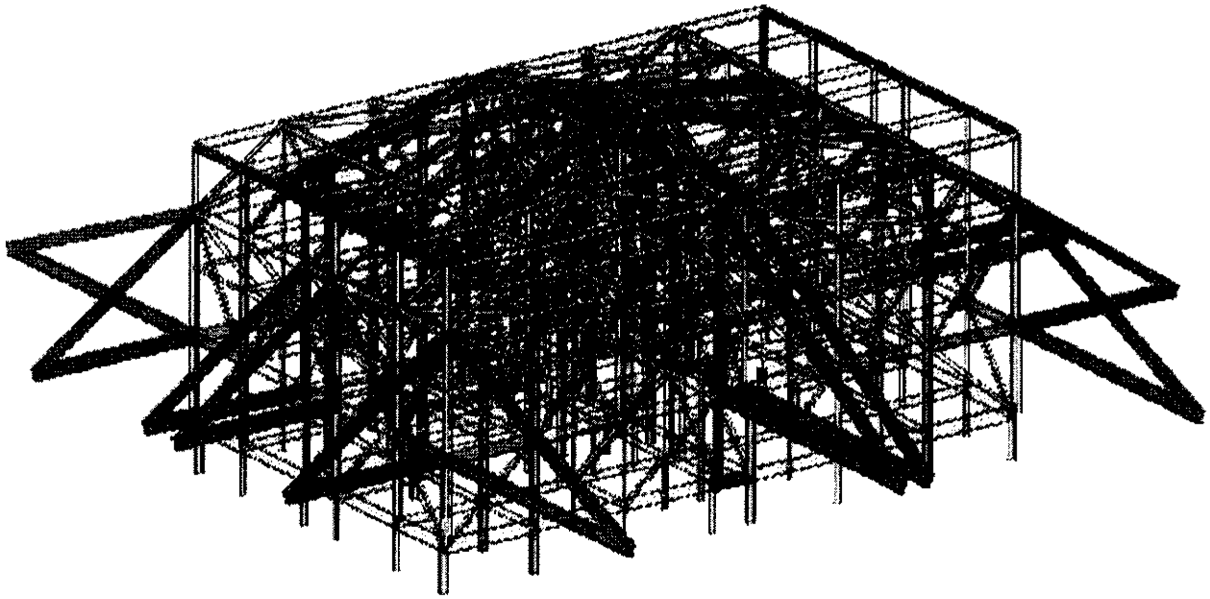


Figure 1–7. Schematic of a hat truss.

Fire Resistance

High-rise buildings in the United States are designed to meet requirements intended, among other objectives, to enable the building to suffer a sizable fire and still remain standing. The requirements are expressed in terms of fire resistance ratings, given in units of time.

The fire resistance of a column, wall, or floor design is rated by subjecting the assembly to standard heating conditions. A sample section of a wall to be tested is installed as one face of a furnace; a floor becomes the top of the furnace. Beams are normally rated as a part of the floor test. Floor systems are always tested while carrying their full design load. Walls are similarly loaded if they are intended to be load bearing, but are not loaded if the only load they are intended to support is their own weight. In the United States, columns are required to be loaded during the test, however, an alternative is often used, whereby the columns is not loaded and the temperature of the steel is used as a limiting criterion.

It is widely recognized in the building profession that fire resistance ratings, although expressed in hours, do not mean that the structure will sustain its performance for that length of time in a real fire. Actual fire performance may be greater or less than that achieved in the test furnace, depending on the severity of the actual fire exposure. Rather, these are taken as relative ratings, e.g., a wall rated at 2 hours will block the spread of a fire longer than a wall rated at 1 hour.

Fire Protection Systems

Bare structural steel components, when exposed to a large and sustained fire, can heat rapidly to the point where their ability to support their load is compromised. Thus, insulation is usually employed to encapsulate the steel and thus delay the heating of the steel. In the WTC towers, a major fraction of the core columns were enclosed or protected on several sides by sheets of gypsum wallboard. The trusses, perimeter columns, spandrels, and one or more surfaces of the core columns were coated with one of

three different sprayed fire-resistive material (SFRM). In this report, these materials are collectively referred to as "insulation."[4] The thickness of the wallboard or the SFRM was selected to provide an intended level of thermal protection. Figure 1–8 shows the appearance of a floor truss with sprayed insulation.

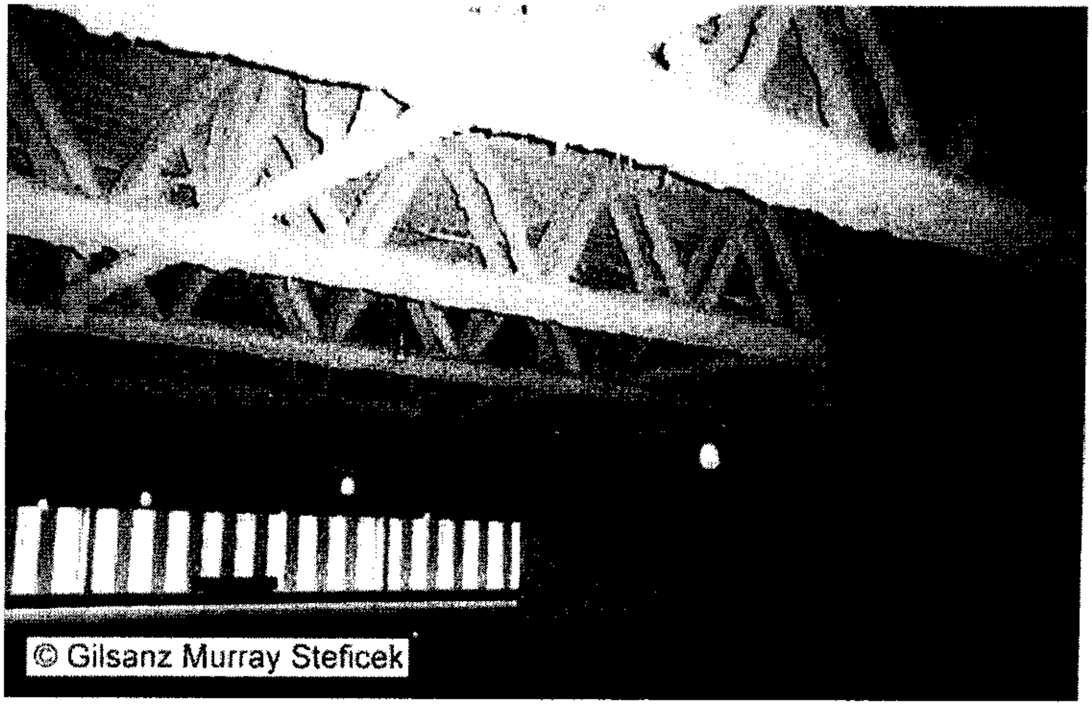


Figure 1–8. Photograph of insulated WTC trusses.

Further protection of the building against a fire was provided in part by internal, nonstructural, fire-rated walls. These floor-slab-to-floor-slab partitions, called demising walls, separated the tenant spaces from each other and from the core area. Their function was to keep a fire from spreading long enough for the fire to be extinguished. In a 1975 fire in WTC 1, these walls significantly confined the fire.

There were three types of nonstructural walls in the towers. The stairwells and elevator shafts were surrounded by 2 in. thick, tongue-and-groove, cast gypsum panels, covered with two or three sheets of 5/8 in. gypsum board. The demising walls were made of two sheets of 5/8 in. thick gypsum wallboard on each side of steel studs. These are often regarded as providing a 2 hour fire separation. Walls in the interior of the tenant spaces generally extended from the floor slab to the bottom of the drop ceiling and were made of single sheets of 5/8 in. gypsum wallboard over steel studs. These walls were not fire-rated. For some conference rooms and other spaces where sound barriers were desired, the walls extended to bottom of the floor slab above, in which case they were regarded as providing a 1 hour fire separation.

In addition to these methods of passive fire protection, there were components that would be activated in the event of a fire. Automatic fire sprinklers had been installed in all of the office spaces. NIST

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[4] The materials used to insulate structural steel are sometimes colloquially referred to as "fireproofing," referring to the intent of the material, rather than the property it imparts. Since an important facet of this Investigation was the determination of the sufficiency of the insulation in protecting the steel from the heat of the fires, this report does not pre-judge the quality of the material by using the colloquial term.

calculations showed that the installed automatic sprinkler system was capable of delivering the minimum required water flow for control of office fires up to 4,500 ft^2. This was a small fraction of the 40,000 ft^2 size floors in the towers. In addition, in the stairwells, there were standpipes (for firefighters to connect their hoses) that were supplied with water by gravity feed from 5,000 gal tanks and by large fire pumps. A multifunction fire alarm system was intended to alert staff at the Fire Command Station within the building and provide voice and strobe alerts throughout. When turned on after the building had been cleared of people, a smoke purge system was intended to purge the hot, opaque fire gases from the building.

However, buildings were not (and still are not) required by the building codes or designed to withstand the impact of a fuel-laden jetliner. Although the impact of a Boeing 707 was stated by the Port Authority to have been considered in the original design of the towers, only one three-page document, in a format typically used for talking points was found that addressed the issue. This document stated that such a collision would result in only local damage and could not cause collapse or substantial damage to the building. NIST was unable to locate any evidence to indicate consideration of the extent of impact-induced structural damage or the size of a fire that could be created by thousands of gallons of jet fuel.

The Workplace

At the beginning of the workday, many of the roughly 40,000 people who worked in the towers and visited to conduct business or to tour emerged from trains in the massive subterranean station. They would take escalators and elevators to a one-story shopping mall, then pass through revolving doors to enter a spacious, 6-story-high lobby on the Concourse Level. There, they would cross paths with those who arrived on foot or by bus or cab.

Getting tens of thousands of people from the Concourse to their offices was no small task. This was accomplished by a combination of express and local elevators located within each of the building cores (Figure 1–9) that was novel at the time of construction.

- People traveling to floors 9 through 40 entered a bank of 24 local elevators at the Concourse Level. These were divided into four groups, with each stopping at a different set of eight or nine floors (9 through 16, 17 through 24, 25 through 31, and 32 through 40).

- Those going to floors 44 through 74 took one of eight express elevators to the 44th floor skylobby before transferring to one of 24 local elevators. These 24 were stacked on top of the lower bank of 24, providing additional transport without increasing the floor space occupied by the elevators.

- Those going to floors 78 through 107 took one of 11 express elevators from the Concourse Level to the 78th floor skylobby before transferring to one of 24 local elevators. These were also stacked on the lower banks of 24 local elevators.

While providing the desired high rate of people movement, this three-tier system used roughly 25 percent less of the building footprint than the conventional systems in which all elevators would have run from the Concourse to the top of the building, resulting in a building core that took up as much as one-half of the floor area. In addition, there was even more rentable space to be gained. At the top of each elevator bank, the machinery to lift the cabs occupied one additional floor. From the next floor up to the bottom of

the next bank, there was no need for an elevator shaft. The concrete floor was extended into this space, providing additional rentable floor area.

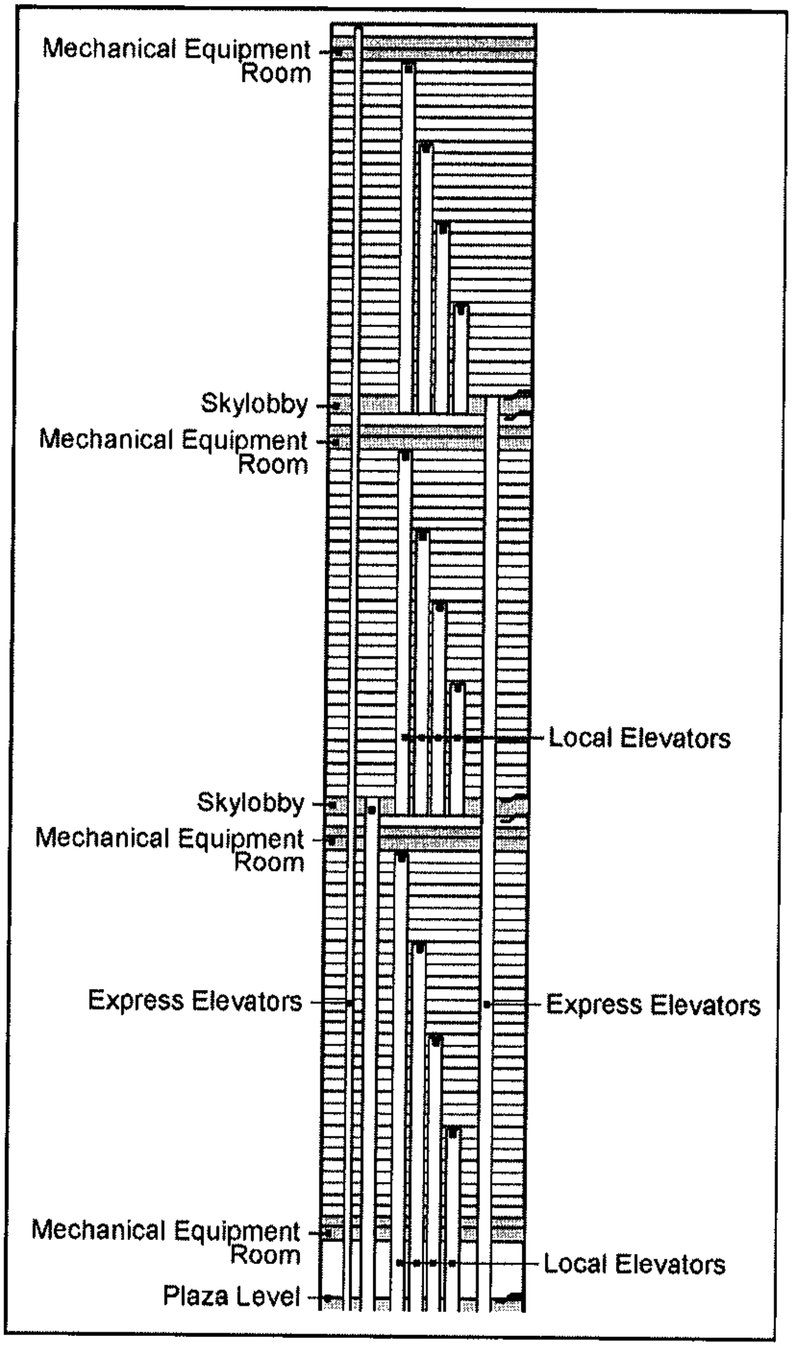

Figure 1–9. Schematic of the three-tier elevator system.

There were two additional express elevators to the Windows on the World restaurant (and related conference rooms and banquet facilities) in WTC 1 and to the observation deck in WTC 2. There were also five local elevators: three that brought people from the subterranean levels to the lobby, one that ran between floors 106 and 110, and one that ran between floors 43 and 44 (in WTC 1), serving the cafeteria

from the skylobby. There were also eight freight elevators, one of which served all floors. All elevators had been upgraded to incorporate firefighter emergency operation requirements.

Also within the core were three sets of stairs that extended nearly the full height of the tower (Figure 1–10). However, the stairwell at an upper floor did not continuously descend to the lobby, but rather to horizontal corridors in the vicinity of the mechanical floors. These enclosed corridors ranged in length from about 10 ft to about 100 ft. (As a result of these and the tiered elevator system, the core arrangements varied substantially from floor to floor.) After traversing each of these, the pedestrians would resume their descent, eventually reaching the tower lobby, from which they could exit the building. The advantages of moving stairwell locations included reclaiming core space for occupant use above terminated elevator shafts and overcoming obstructions posed by equipment installed on mechanical floors.

> Following the February 26, 1993, bombing of WTC 1 and in light of the 4 hours needed to evacuate the building, several improvements had been made to the stairwells: battery operated emergency lighting, photoluminescent floor strips indicating the path to be followed, and explicit signs on each doorway to indicate where it led.

Upon exiting the elevators or stairs, the interior view was typical of high-rise buildings. Surrounding the rectangular core corridor was a mixture of walls, entry doors to firms, and glass-front reception areas. Above was a drop ceiling.

Many of the floors were occupied by a single tenant. Some of these tenants occupied multiple floors. By 2001, most of these companies had moved in after the installation of automatic sprinklers, which had allowed the absence of internal partitions. These companies largely took advantage of Yamasaki's design concept of a vast space that was nearly free of obstructions. The open arrangement often included as many as 200 or more individual modular workstations or office cubicles, generally clustered in groups of six or eight (Figure 1–11). Trading floors had arrays of tables with multiple computer screens (e.g., Figure 1–12, of a trading floor in WTC 4). Some of these floors had a few executive offices in the corners and along the perimeter. Many also had walled conference rooms. It was common for the tenants occupying multiple floors to create openings in the floor slabs and install convenience stairs between their floors.

Some floors were subdivided to accommodate as many as 20 firms. Some of the smaller firms occupied space in the core area in the spaces over the elevator shafts.

With thousands of workers and visitors in the buildings, there needed to be food service. The Port Authority maintained a cafeteria on the 43rd floor of WTC 1. In addition, a number of the companies maintained kitchen areas on their floors, where catered food was brought in daily, making it unnecessary for their staff to leave the building for lunch. There was a public cafeteria on the 44th floor of WTC 1. The visiting public could eat at Windows on the World at the top of WTC 1, at several restaurants on the observation deck of WTC 2, or in the many eateries on the Concourse Level. There were hundreds of restrooms, in both the tenant and the core spaces.

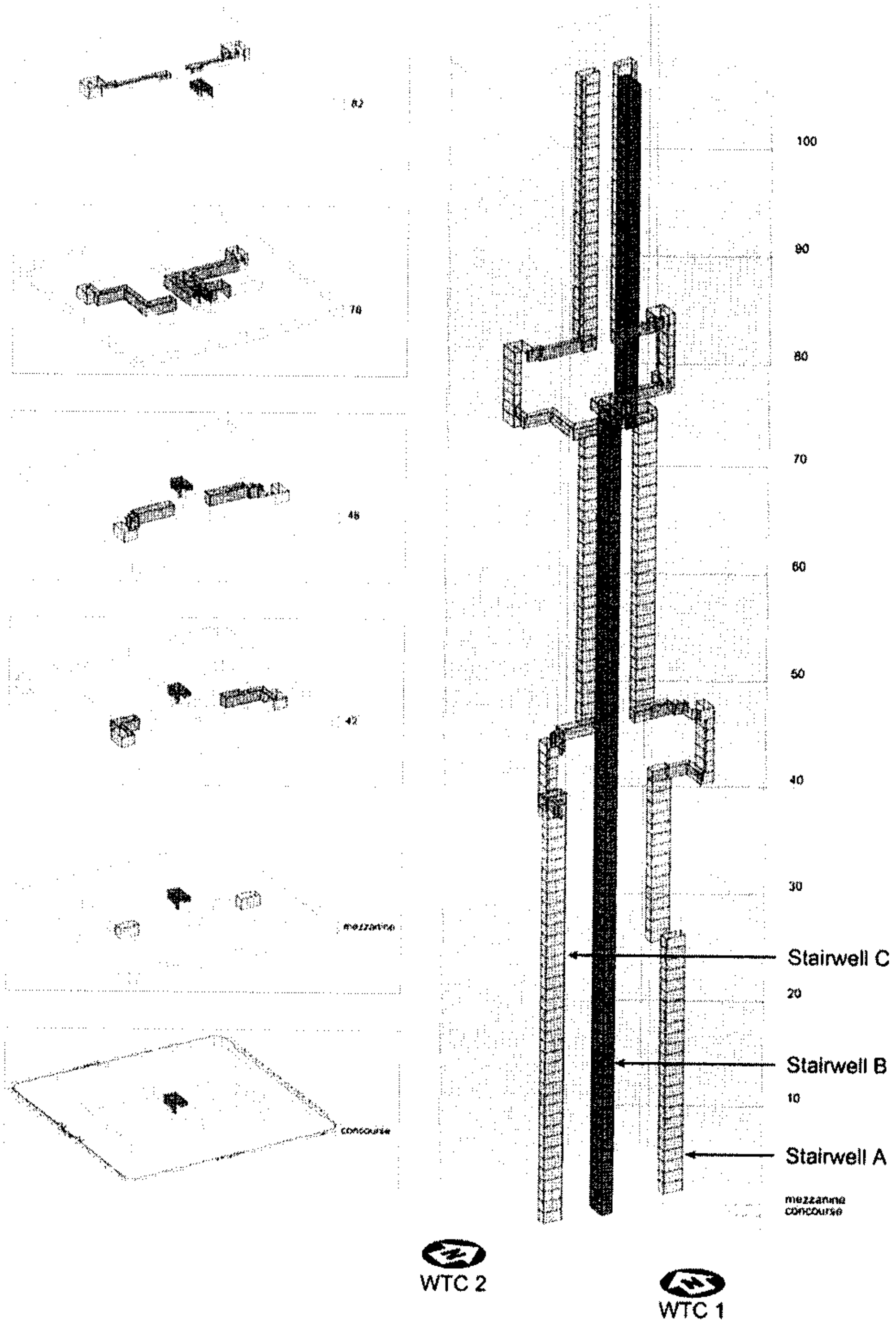

Figure 1–10. Orientation of the three stairwells.

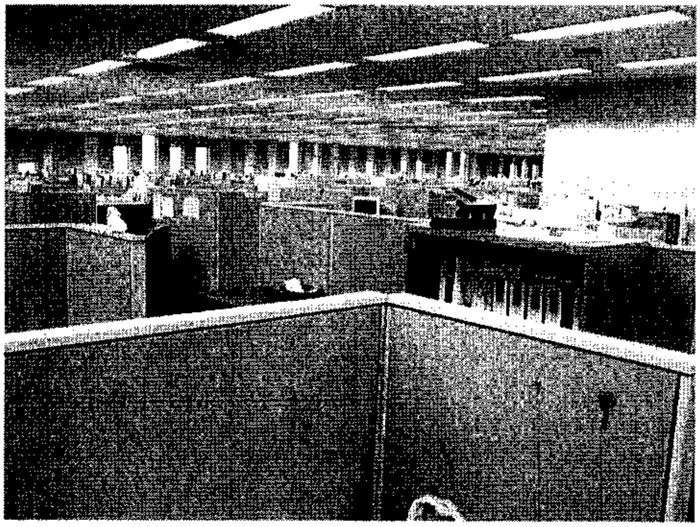

Figure 1–11. Views of typical WTC office floors.

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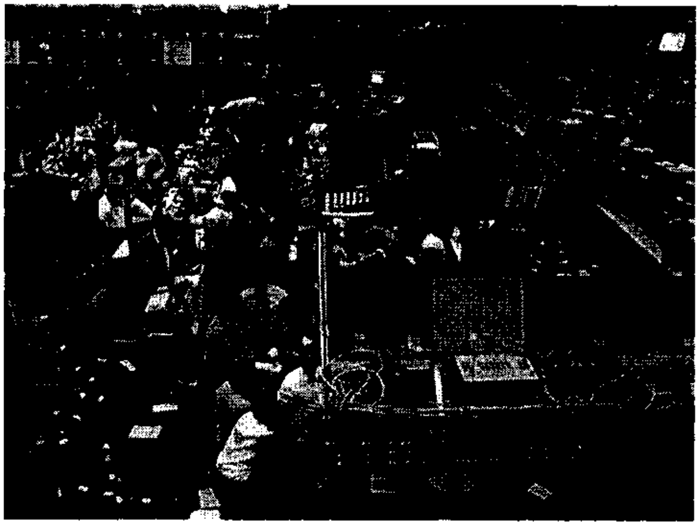

Figure 1–12. A WTC trading floor.

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